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INVESTIGATION OF THE IMPACT OF HIGH-FINENESS-RATIO PROJECTILES INTO THICK TARGETS

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SUMMARY

Tests were conducted to determine the penetration of high-fineness-ratio projectiles into thick targets. The projectiles were copper rods with diameters of 0.0044 inch, 0.0029 inch, 0.0014 inch, and 0.0007 inch, and lengths of 0.200 inch, 0.300 inch, 0.500 inch, 0.700 inch, and 0.750 inch. Fineness ratios ranged from 69 to 1000. Targets were 1/2-inch- and 5/8-inch-diameter 2017-T4 aluminum spheres. Impacts occurred at a nominal velocity of 15,000 feet per second. Projectile inclination angles were varied from end-on to broadside.

A partially theoretical equation which correlates the effects of length, diameter, and inclination on the maximum depth of penetration was found.

The effect of projectile curvature was investigated for 0.0029-inch-diameter copper projectiles of fineness ratio 259. Three different radii of curvature, R = 0.5 inch, R = 1.0 inch, and R = 3.0 inches, and three different orientations for each curvature were tested. Although curvature drastically reduced maximum penetration at zero inclination, this reduced penetration was maintained approximately constant over a large range of projectile inclinations so that at large inclinations, the curved projectiles penetrated more deeply than the straight projectiles.

INTRODUCTION

A program of research directed toward determining the damage produced by the impact of high-fineness-ratio projectiles upon structures is being conducted at the NASA Ames Research Center. In the first phase of this investigation (ref. 1), the effect of projectile angle of inclination upon depth of penetration was presented for 0.0025-inch-diameter copper projectiles with a fineness ratio of 300, impacting aluminum targets at 15,000 feet per second. Two types of craters were observed, depending upon the inclination of the projectile - deep and narrow for near end-on impacts and shallow and long for impacts at large inclinations. The transition from end-on to broadside-type craters was very abrupt and, for the specific projectiles investigated, occurred within the inclination range from 4° to 5°. The projectile curvature also appeared to drastically reduce the maximum penetration of end-on-type impacts but to have very little effect upon the penetration at large inclinations.

The purpose of the present report is to extend the data to cover a much wider range of projectile fineness ratios and, consequently, to determine the effect of projectile diameter and length upon depth of penetration for inclined projectiles. Data relating projectile radius of curvature to depth of penetration and angle of inclination are also presented and compared with that for straight projectiles with the same fineness ratio.

TEST PROCEDURE

The tests were conducted by firing 1/2-inch- and 5/8-inch-diameter 2017-T4 aluminum spheres from a light-gas gun into high-fineness-ratio copper rods suspended on nylon strands directly in the path of the model. The copper rods will be referred to as projectiles and the spheres as targets even though in these tests, it was the target that was in motion. The sphere targets were mounted in nylon sabots during launch and the sabot and target were aerodynamically separated before impact with the projectile occurred. After impact, the targets were aerodynamically decelerated and recovered in a polystyrene-foam and cotton-waste catcher located at the end of the flight test chamber. The targets were then sectioned and microscopically examined to determine the impact damage. More complete details of the test apparatus and setup as well as the techniques used are described in reference 1.

The copper projectiles varied in length from 0.200 to 0.750 inch with diameters of 0.0007 inch, 0.0014 inch, 0.0029 inch, and 0.0044 inch (fineness ratios from 69 to 1000). The 0.0029-inch-diameter projectiles with a fineness ratio of 259 were curved to radii of 0.5 inch, 1.0 inch, 3.0 inches, and ∞ (straight). For each of the curved projectiles, three different orientations were tested, as will be discussed later.

DISCUSSION OF RESULTS

Effect of Projectile Fineness Ratio and Angle of Inclination

The angle of projectile inclination, defined as the angle between the projectile longitudinal axis and the flight trajectory, is independent of the obliquity, defined as the angle between the trajectory and the radius vector of the target at the point of impact (a definition consistent with the usual definition of obliquity for impact work). The maximum depth of penetration is measured from the target surface parallel to the trajectory and thus is not dependent upon target obliquity.

The penetration of high-fineness-ratio copper projectiles into aluminum targets is presented in figure 1. The penetration, in units of projectile length, is plotted versus the inclination angle, in degrees. The data shown represent impacts by projectiles with diameters of 0.0044, 0.0029, 0.0014, and 0.0007 inch, and fineness ratios of 69, 103, 170, 259, 536, 714, and 1000. The abscissa covers inclination angles to 30° since this is the test range where most of the data were acquired. Flagged symbols indicate that the targets were completely penetrated by the projectile so that the corresponding

penetrations are probably deeper than shown. All impacts occurred at velocities near 15,000 feet per second and no velocity adjustments were made.

During the data-reduction process it was noted that the measured depth of penetration was very sensitive to the accuracy of the crater-sectioning process. If a target was not perfectly cross-sectioned, the penetration measurements and crater profile appearance were seriously impaired. If, on the other hand, the crater was accurately sectioned, the crater profile was quite distinct and crater depth measurements were accordingly more accurate. Thus, certain of the data of figure 1 are more reliable than others. In addition, many targets suffered distinct damage from the nylon strands used to support the test projectile (fig. 2). When the target is positioned so that this damage gives the projectile-target orientation at impact, microscopic measurements of the distance between the damage from adjacent strands enable projectile inclinations to be re-evaluated to within about 10 minutes of arc. The data of figure 1, representing the more reliable measurements, are indicated by the closed symbols.

The data for end-on impacts in figure 1 show that there is more scatter than might be expected and that the penetrations are frequently less than those for slightly inclined impacts. These considerations indicate that these impacts are quite sensitive to imperfections in the test setup. This result indicates that perfect end-on impacts might produce craters considerably deeper than any that were observed.

When the end-on impact of high-fineness-ratio projectiles is compared to that of the constant density jets considered in shaped-charge jet theory, it is clear that the two projectiles are in many respects equivalent. The penetration of high-fineness-ratio projectiles striking end-on therefore may be assumed to be given by the shaped-charge jet equation. The penetration formula derived by application of shaped-charge jet theory in reference 2, under the assumptions that (a) the impact pressures are large compared to the strength of the target and jet, (b) a steady-state penetration rate is reached almost instantaneously upon impact, and (c) the penetration stops as soon as the last jet particle has struck the target, is

$$p = l\sqrt{\frac{\rho_P}{\rho_T}} \tag{1}$$

where p is the penetration, l is the projectile length, ρ_P is the density of the projectile, and ρ_T is the density of the target. This formula states that the penetration is independent of velocity and projectile diameter, and depends only on the densities of the target and projectile and the length of the projectile. The projectile diameter influences only the diameter of the crater produced.

For a projectile with a given fineness ratio, as the inclination is increased, some of the projectile length no longer falls into the crater produced by the projectile leading element. This "extra" length cannot contribute to the crater's maximum depth. As the inclination increases even further,

less of the projectile length falls into the original crater and penetration decreases systematically as inclination increases.

Moreover, at a given angle of inclination (other than end-on) and for a particular projectile length, as the fineness ratio increases, less projectile length can fall into the original crater by virtue of the crater's smaller diameter, and penetration thus decreases. In addition, for a constant diameter projectile, increasing the projectile length adds nothing to the maximum crater depth if the angle is such that the additional length falls outside the original crater. The longer length does decrease the value of the penetration to length ratio, however. Consequently, regardless of the changes in projectile dimensions necessary to increase the fineness ratio, the penetration to length ratio decreases with increase in fineness ratio at any angle of inclination greater than zero.

The data of figure 1 are fitted by the equation

$$\frac{p}{l} = \sqrt{\frac{\rho_p}{\rho_T}}\left[\frac{1}{1 + 0.01(l/d)^{3/2}\theta^{2/3}}\right] \tag{2}$$

where θ is the inclination angle in radians. The calculated curves are in qualitative agreement with the data.

Consider the case where the projectile diameter is held constant and the length is allowed to vary. Intuitively, as the angle of inclination is increased, the contribution of length to penetration must decrease. Ultimately, at broadside impact, the length must have little, if any, effect on penetration. Curves on a plot of penetration versus inclination would be expected to merge at that inclination where length becomes ineffective. Figure 3 compares curves calculated from equation (2) with a number of data points. The curves represent a fair fit to the limited data shown. The effect of length on penetration at large inclination angles as given by equation (2) is seen to be a small one and is the reverse of what would be expected since the short projectile is calculated to penetrate deeper than the long one. (Compare, e.g., the curves for 0.750-inch and 0.300-inch lengths above $\theta = 3.2^{\circ}$.) This defect in the equation is not a serious one, however, since to a first order of approximation, the penetrations of the two lengths are equal, as they should be at large inclinations. However, because of this defect, the applicability of equation (2) is arbitrarily limited to inclinations less than those of these tests, that is, to inclination angles less than 30°.

Figure 4 is a plot of the penetration to length ratio versus the inclination angle for the complete inclination range. The segments of the curves from 0° to 30° inclination are calculated from equation (2) using the fineness ratios of the projectiles of figures 1 and 3. Several broadside impact data points are plotted and the calculated curves for projectiles with these fineness ratios are extended to 90° (solid curves). It can be seen that the broadside impact data points are as much as 40 percent lower than predicted by equation (2). The measured penetrations correspond closely to the

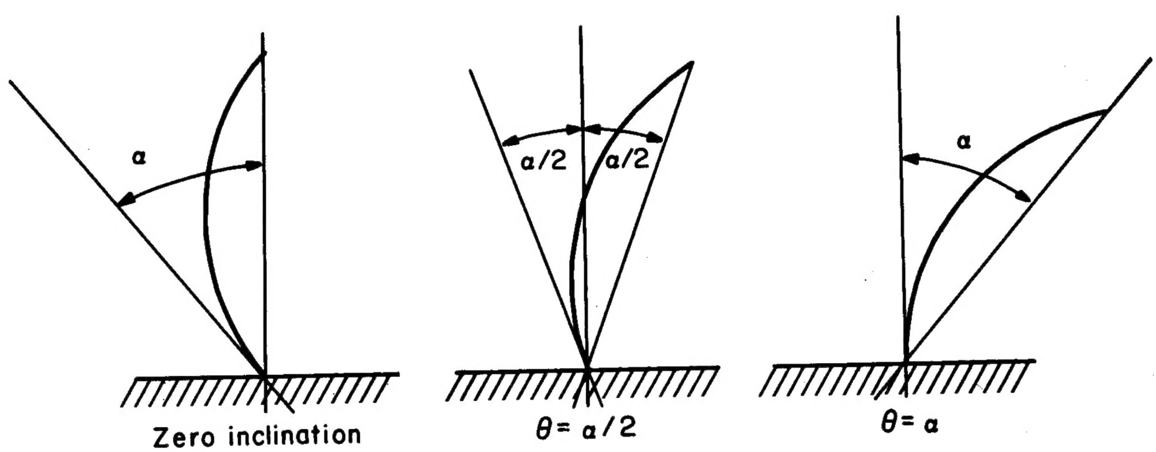
penetrations resulting from the impact of spheres, of the same diameters as those of the high-fineness-ratio projectiles tested, as given by the Ames penetration equation (see ref. 3)

$$\frac{p}{l} = 2.28 \left(\frac{d}{l}\right)\left(\frac{\rho_P}{\rho_T}\right)^{2/3}\left(\frac{V}{c}\right)^{2/3} \tag{3}$$

where V is the impact velocity and c is the speed of sound in the target material, the velocity of propagation of a plane longitudinal wave in a slender prismatic bar. Since the available broadside impact data can be expressed by equation (3), this equation was used to calculate the penetration to length ratios for broadside impact for the remaining fineness ratios of figure 4. The dashed curves covering the inclination range from 30° to 90° were obtained by simply fairing curves for each projectile fineness ratio to obtain a smooth transition from the curves at 30° to the corresponding penetration to length ratios at 90°.

Effect of Projectile Curvature

The three projectile orientations investigated for each curvature are illustrated in sketch (a). They are denoted by inclination angle arbitrarily measured relative to the chord of the curved projectile. The angle, α, remains constant for any one projectile curvature. Clearly, the projectile



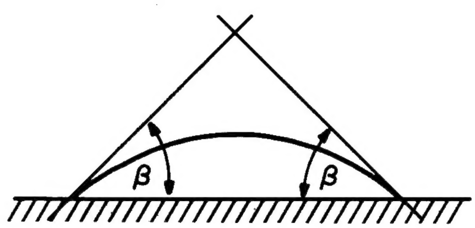
Sketch (a)

orientation that would produce the maximum penetration is included within the orientation range of this program. As the orientation of the curved projectile ranges from zero inclination to $\theta = \alpha$, the angle that the tangent to the leading end of the projectile makes with the target normal varies through an inclination range of 43° for the 0.5-inch radius of curvature, 21.5° for the 1.0-inch radius of curvature, and 7° for the 3.0-inch radius of curvature.

The penetration data for the curved projectiles are presented in figure 5. Plotted is the penetration to length ratio as a function of angle of inclination. The three orientations for each radius of curvature are plotted at their respective angles of inclination, as defined above. The curve shown in figure 5 represents the penetration data of the corresponding straight projectile with the same fineness ratio from figure 4.

Comparing the maximum penetration of the curved projectiles to the maximum penetration of the straight projectile shows that curvature drastically reduces the maximum penetration. The maximum penetration of the curved projectiles in these tests corresponds to the penetration of a straight projectile of the same fineness ratio impacting at an inclination angle of about 3.5°. On the other hand, figure 5 shows that projectile curvature tends to maintain penetration at a high level over a large inclination range. For curved projectiles, the penetration remains essentially constant throughout the inclination-angle range tested. As the inclination increases even further, it seems reasonable to expect that the penetration will be a function of the larger of the angles that the tangent to either end of the projectile makes with the target normal.

When the attitude becomes that shown in sketch (b), the minimum penetrations of curved projectiles with radii of curvature of 0.5 inch, 1.0 inch, and 3.0 inches should correspond to that of equal-fineness-ratio straight projectiles impacting at an inclination of 47°, 68.5°, and 83°, respectively. Penetration values for these inclinations have been taken from the curve of figure 4 and are plotted as the filled symbols to represent the curved projectiles impacting at 90° inclination.



Sketch (b)

Finally, it is clear that the results of this series of tests must no longer hold when the radius of curvature is so large that all of the projectile falls into the crater made by the projectile leading element or when the radius of curvature is so small that the projectile begins to overlap itself. No attempt has been made to study these limiting curvatures, however.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Oct. 28, 1965

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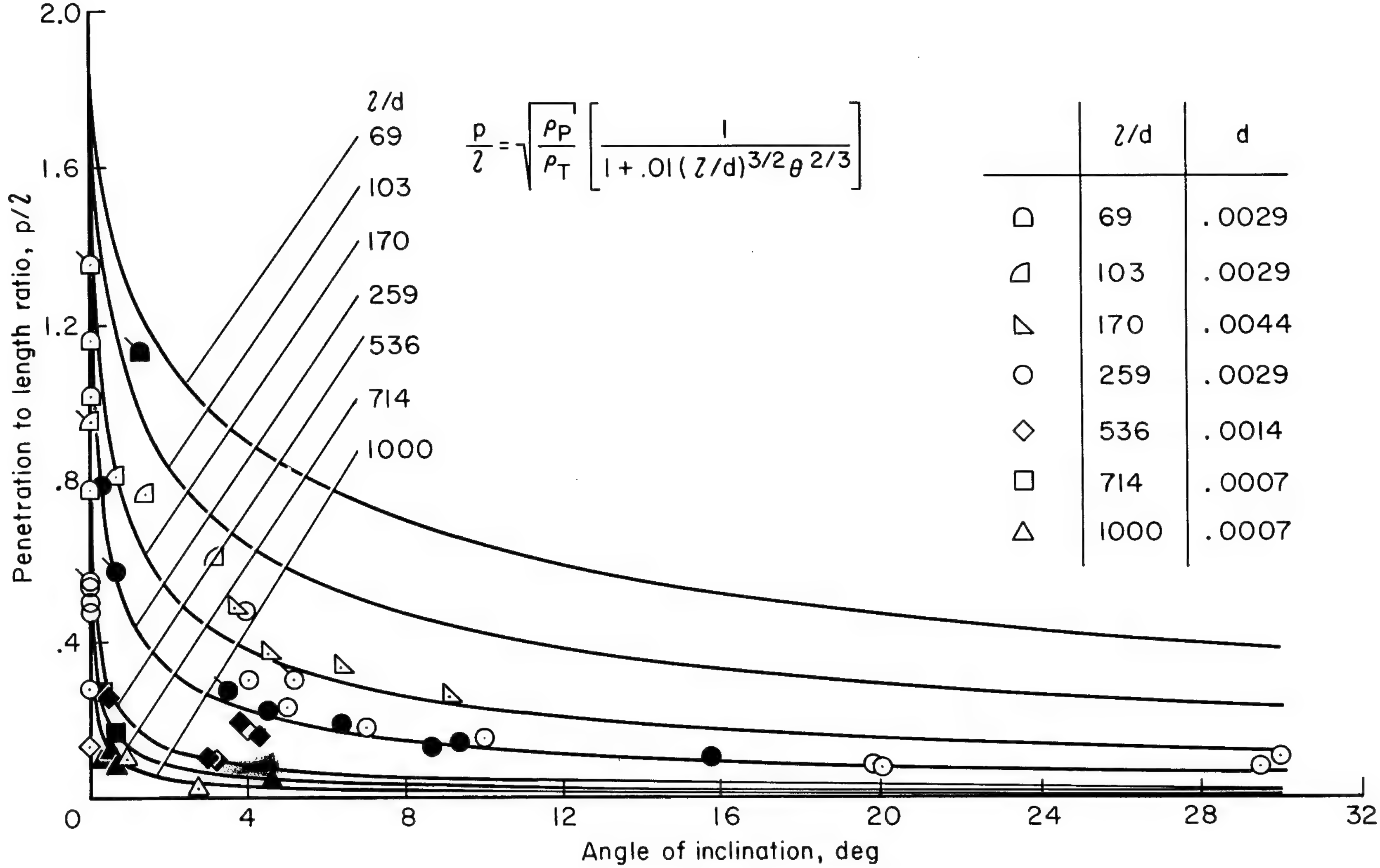

Figure 1.- Variation of penetration to length ratio with angle of inclination and projectile fineness ratio.

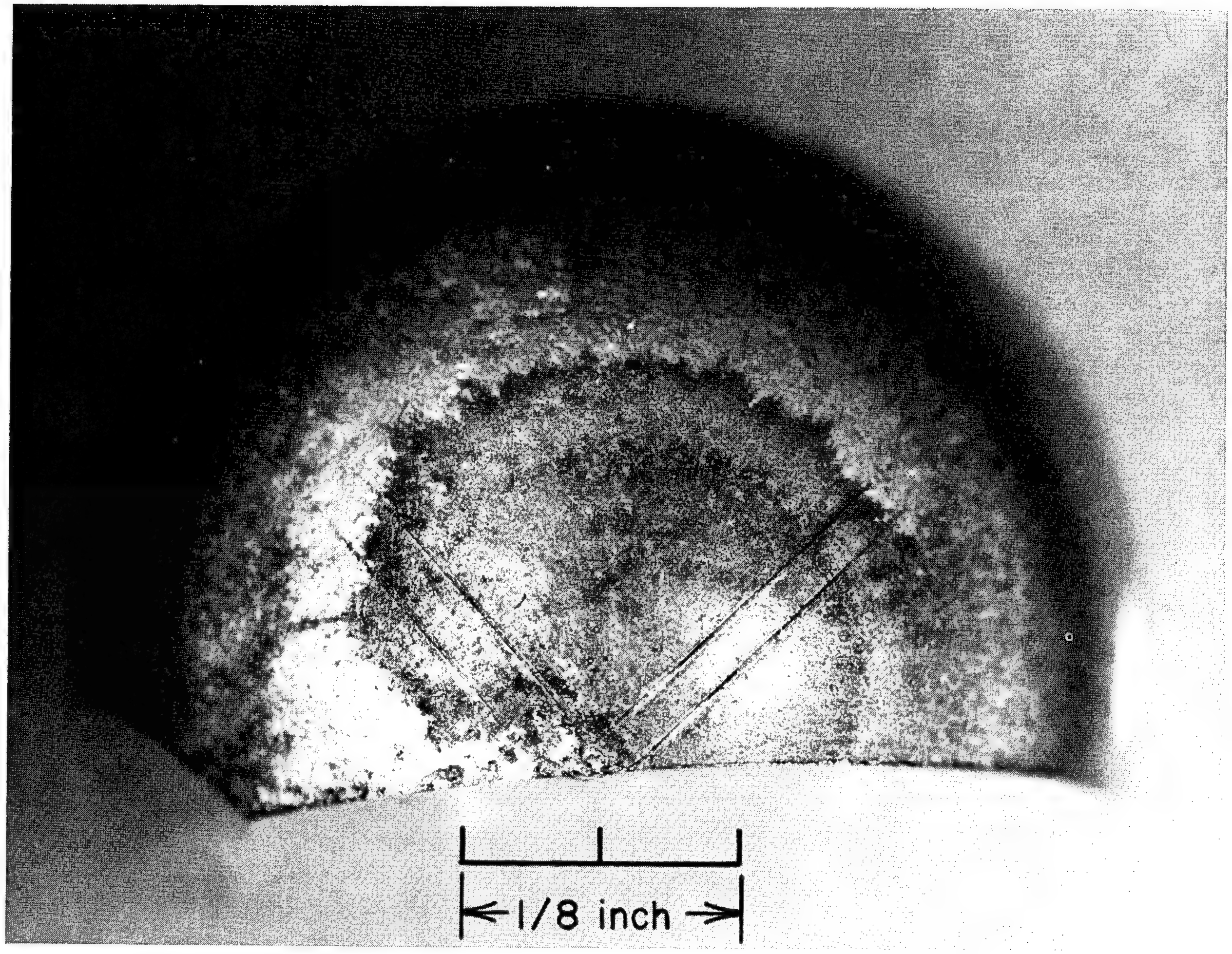

Figure 2.- Photograph of target showing nylon supporting strand damage.

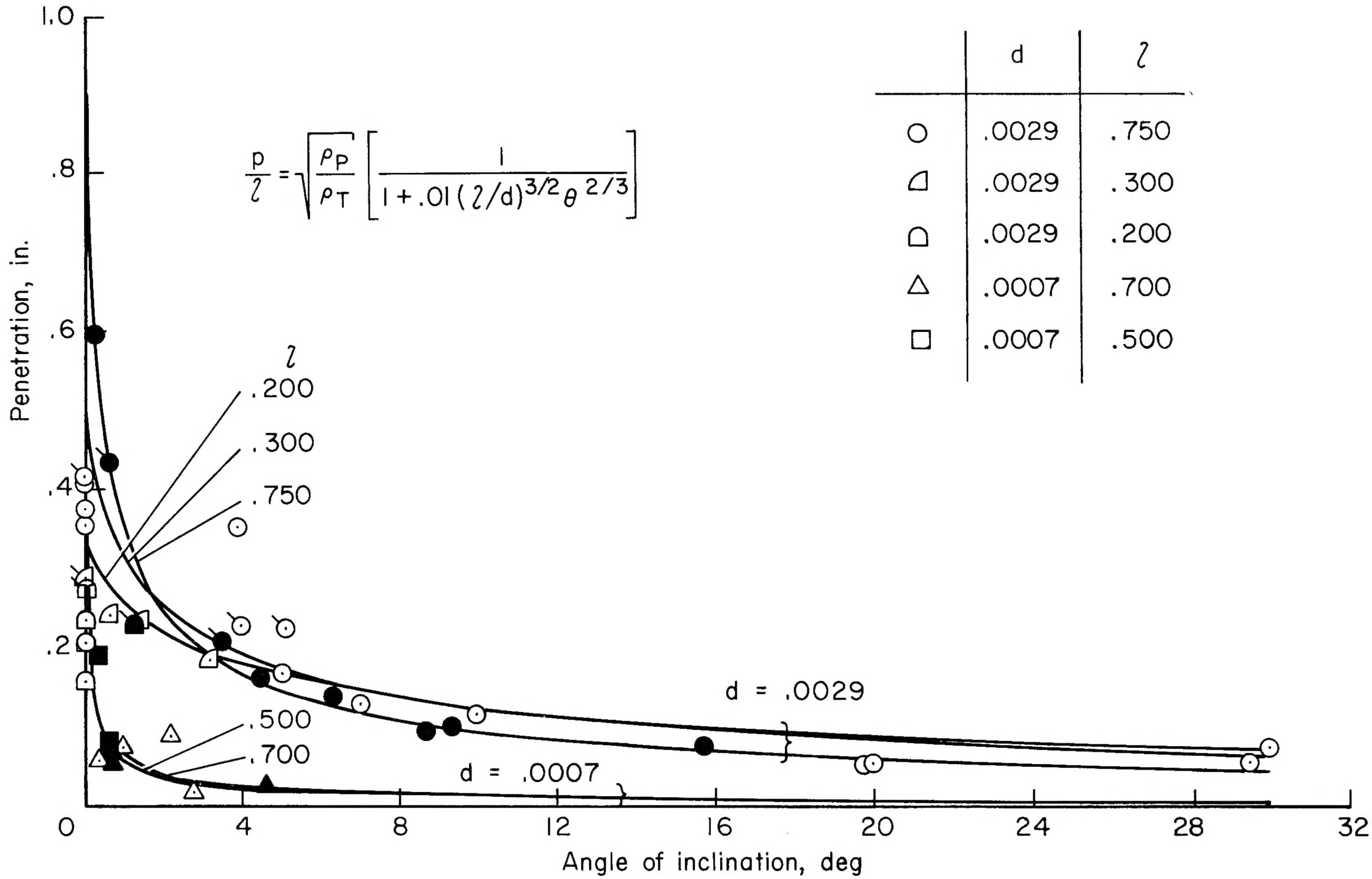

Figure 3.- Effect of projectile length on penetration.

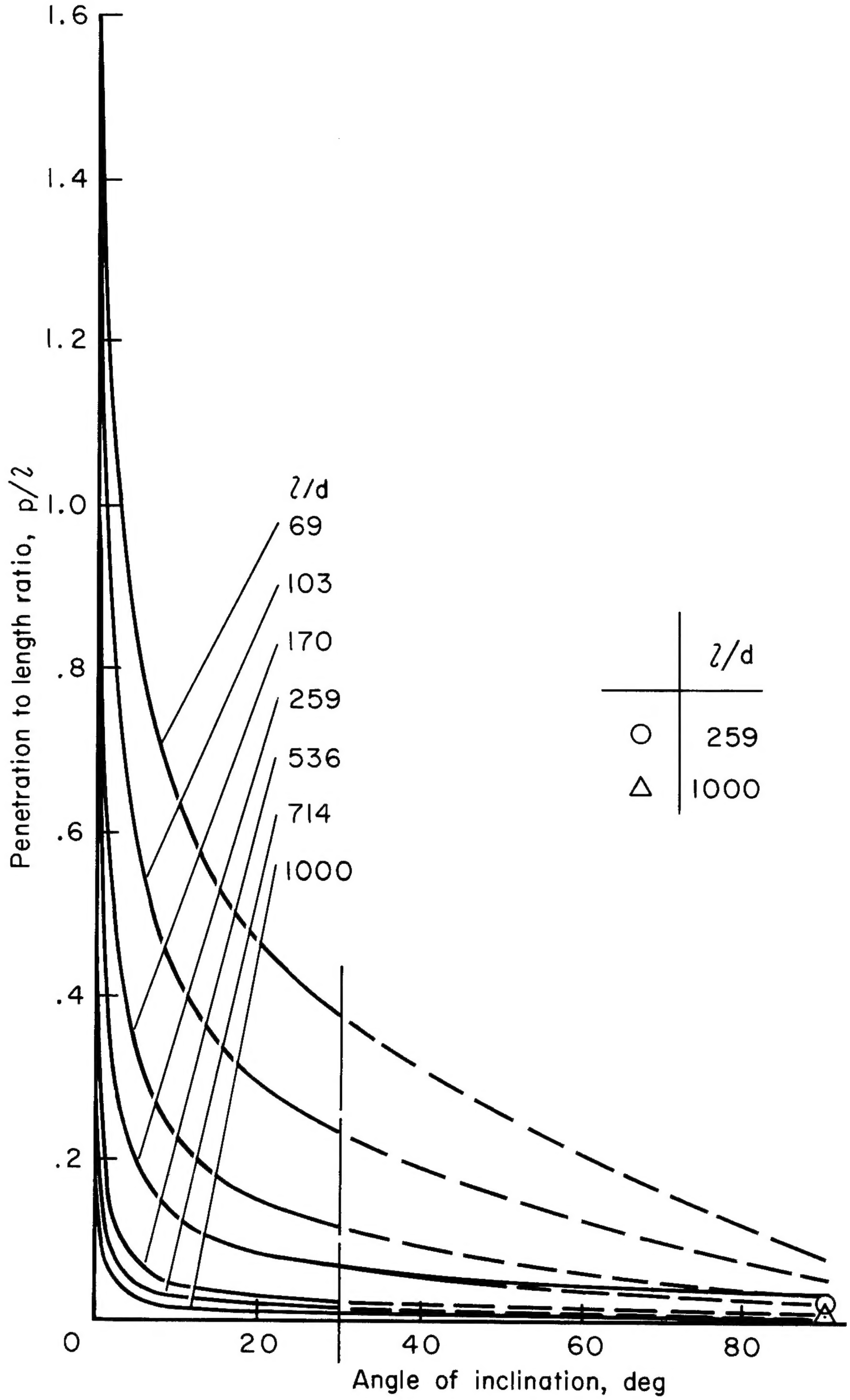

Figure 4.- Effect of projectile fineness ratio upon penetration.

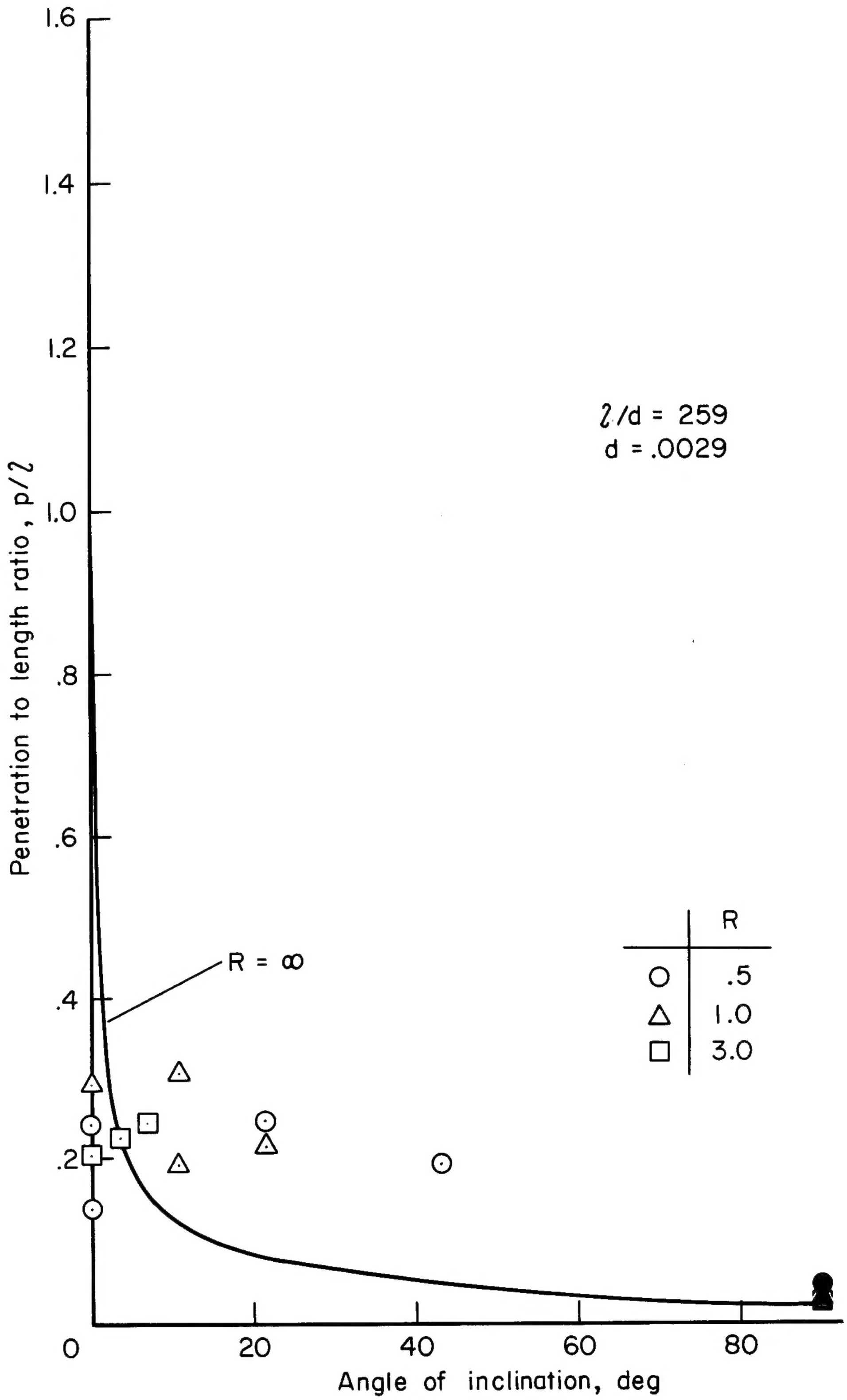

Figure 5.- Effect of radius of curvature upon penetration.

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